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10/509553
DT05 Rec'd PCT/PTO 28 SEP 2004

Description

Method for fabricating a reference layer and MRAM memory cell provided with a reference layer of this type

The invention relates to a method for fabricating a reference layer for MRAM memory cells and to an MRAM memory cell having a reference layer fabricated in this way.

As is known, an MRAM arrangement is based on ferromagnetic storage with the aid of the TMR effect (TMR = tunneling magnetoresistance). The accompanying Figure 1 shows a diagrammatic cross section through a known MRAM memory cell that utilizes said TMR effect. The TMR memory cell, comprising a layer stack having a soft-magnetic layer 2, a tunnel oxide layer 3 and a hard-magnetic or reference layer, lies between a bit line 5 and a word line 4, which cross one another. The magnetization direction (arrow) of the hard-magnetic layer 1 is predetermined, while the magnetization direction (double arrow) of the soft-magnetic layer 2 is adjustable by sending corresponding currents I, I' in different directions through the word line 4 and the bit line 5. These currents enable the magnetization of the soft-magnetic layer 2 to be polarized parallel or antiparallel with respect to the magnetization direction of the hard-magnetic layer 1. The resistance of the layer stack is lower in the case of parallel magnetization of the two layers 1 and 2 than in the case of antiparallel magnetization, which can be evaluated as state "0" and "1", or vice versa.

Since the net magnetization of the reference layer determines the overall behavior of the MRAM memory cell, it is desirable to make said net magnetization adjustable in a targeted manner during the fabrication of MRAM memory cells.

It is accordingly an object of the invention to specify a method for fabricating a reference layer for MRAM memory cells and an MRAM memory cell equipped with a reference layer

fabricated in this way, such that the net magnetization of the reference layer and thus the overall behavior of the MRAM memory cell can be established in a targeted manner.

A method for fabricating a reference layer for MRAM memory cells which achieves this object is characterized, according to the invention, by the following steps:

(A) a layer system is provided for the reference layer, which layer system has a first layer of a material having a first Curie temperature T_C^1, which first layer can be permanently magnetized by an external magnetic field, and a second layer of a material having a second Curie temperature T_C^2, which is significantly lower than the first Curie temperature T_C^1, which second layer can be magnetized by antiferromagnetic coupling with the first layer;

(B) an external magnetic field is generated;

(C) the layer system is cooled from a temperature above the first Curie temperature T_C^1 to below the first Curie temperature T_C^1 by action of the external magnetic field, the field strength of the external magnetic field being greater than the saturation field strength of the first layer, so that the magnetization of the first layer is oriented by a second-order phase transition along the field direction of the external magnetic field; and

(D) the layer system is subsequently cooled below the second Curie temperature T_C^2, the magnetization of the second layer being oriented antiparallel with respect to the magnetization of the first layer on account of antiferromagnetic coupling between the first and second layers.

Accordingly, a, for example symmetrical, artificial antiferromagnet (AAF) is proposed for the reference layer, said antiferromagnet having the two antiferromagnetically coupled layers that differ in their Curie temperature. When cooling from a temperature above the first Curie temperature T_C^1 in an externally applied magnetic field, the

magnetization of the first layer of the layer system is oriented by a second-order phase transition along the field direction of the external magnetic field provided that the external field strength is greater than the saturation field strength for the first layer. Upon further cooling to below the second Curie temperature T_C^2, the magnetization of the second layer is oriented antiparallel with respect to the magnetization direction of the first layer as a result of the antiferromagnetic coupling between the two layers. As a result, the two layers, that is to say the first layer and the second layer, form an artificial antiferromagnet (AAF).

What is crucial is the generation of the magnetization distribution in the second layer by the second-order phase transition at the lower Curie temperature T_C^2 of the second layer. The magnetization distribution present in the first layer is transferred to the second layer by the existing coupling (antiparallel) by antiferromagnetic coupling.

If the net magnetizations (saturation flux = saturation magnetization x layer cross section) of the first and second layers are in each case chosen correspondingly, it is possible to set a net magnetization of the layer system of zero, that is to say that the magnetization within the artificial antiferromagnet thus produced should therefore be largely stable with respect to external fields as long as the magnetic coupling between the individual layers is strong enough.

Furthermore, the net magnetization of the layer system can also be set controllably in a targeted manner, for example by choosing the saturation magnetization or the layer cross section of the second layer to be smaller than that of the first layer. Consequently, in the event of dispensing with the advantage of a symmetrical artificial antiferromagnet in the case of which the two layers have identical saturation flux, it is possible to use the proposed layer construction for fabricating an inverse artificial antiferromagnet. In the

TMR memory cell, the thinner layer is then in contact with the tunnel barrier. The problem that exists with the customary construction, where residual 360° walls attenuate the signal, is obviated since each layer is inherently saturated and therefore has no 360° walls.

A homogeneous magnetization of the first layer that is obtained in step (C) can also be transferred to the second layer by intermediate layer coupling. That is to say that in step (A), a layer system is provided which has a very thin intermediate coupling layer between the first and second layers. This has the advantage, inter alia, that no 360° walls occur in the second layer when the first layer is saturated.

The following material combinations, in particular, are preferred for the first layer and the second layer of the proposed layer system:

(a) First layer: $(Co,Fe,Mn)_{80}(Si,B)_{20}$ having the Curie temperature T_C^1 = 485°C and second layer: $(Co,Fe,Mo)_{73}(Si,B)_{27}$ having the Curie temperature T_C^2 = 210°C. A soft/soft magnetization behavior is achieved overall with this material combination.

(b) First layer: $(Co,Fe)_{83}(Si,B)_{17}$ having the Curie temperature T_C^1 = 415°C and second layer: $(Ni,Fe)_{78}(Si,B,C)_{22}$ having the Curie temperature T_C^2 = 260°C. This material combination enables a magnetostrictive behavior of the layer system.

(c) First layer: $Tb_{20}Fe_{40}Co_{40}$ having the Curie temperature T_C^1 = 400°C and second layer: $Tb_{20}Fe_{80}$ having the Curie temperature T_C^2 = 150°C. This enables a ferrimagnetic behavior of the layer system.

Materials of the intermediate layer may be ruthenium, copper or gold.

The magnetic coupling between the first layer and the second layer depends on the thickness of the intermediate layer, which must be chosen such that the antiferromagnetic coupling takes place.

A reference layer fabricated by this method and an MRAM memory cell equipped with a reference layer of this type have the following advantages, in particular:

- targeted setting of the magnetization distribution in the individual layers;
- vanishing net magnetization or a net magnetization of the layer system that can be controlled through choice of the saturation magnetization and the thickness of the first and second layers;
- when the first layer is frozen, the magnetization of the second layer is not active (above T_C^2);
- transfer of the homogeneous magnetization from the first layer to the second layer by the intermediate layer coupling mentioned. This has the advantage, inter alia, that no 360° walls should occur in the second layer when the first layer is saturated;
- in the event of dispensing with the advantage of the symmetrical artificial antiferromagnet in the case of which the two layers have an identical saturation flux, it is possible to use the proposed layer construction for fabricating an inverse artificial antiferromagnet. The problem that exists with the customary construction of an MRAM memory cell where residual 360° walls attenuate the signal is obviated since each layer is inherently saturated and therefore has no 360° walls.

The description below describes, with reference to the drawing, exemplary embodiments of a method according to the invention and of an MRAM memory cell equipped with such a reference layer. In detail, in the figures of the drawing:

Figure 1 shows a diagrammatic cross section through the known structure of an MRAM memory cell that has already been explained;

Figures 2A and 2B show diagrammatic cross sections through a first and a second exemplary embodiment of an MRAM memory cell having a reference layer fabricated according to the invention;

Figure 3 shows a diagrammatic cross section through a third exemplary embodiment of a further MRAM memory cell equipped with another reference layer according to the invention, and

Figure 4 diagrammatically shows a diagram for elucidating the method according to the invention for fabricating the reference layer.

In the case of the MRAM memory cells according to the invention that are illustrated diagrammatically in Figures 2A and 2B, a layer stack comprising two layers 10 and 11, which form a reference layer system R according to the invention, a tunnel barrier 13 and a soft-magnetic layer 12 lies between a word line (WORDL) 14 and a bit line (BITL) 15. In Figure 2A, the first layer 10 and the second layer 11 of the layer system R in each case have the same saturation magnetization and the same layer cross section, so that a net magnetization of the layer system R results as zero.

By contrast, in Figure 2B, the first layer 10 and the second layer 11 of the layer system R of the reference layer have a different net magnetization by virtue of the layer cross section of the second layer 11 being chosen to be smaller than that of the first layer 10. The thinner second layer 11 is in contact with the tunnel barrier 13. Since each layer, that is to say the first layer 10 and the second layer 11, are inherently saturated and therefore have no 360° walls, the problem that exists with the known construction of an

MRAM memory cell where residual 360° walls attenuate the signal is obviated.

In the case of the third exemplary embodiment illustrated in the form of a diagrammatic cross section in Figure 3, the layer system R' of the reference layer has a construction comprising a first layer 100, a thin intermediate coupling layer 102 and a second layer 101. By virtue of said intermediate coupling layer 102, the homogeneous magnetization of the first layer 100 is transferred to the second layer 101 through the coupling of the intermediate coupling layer 102. As a result, no 360° walls occur in the second layer when the first layer is saturated. For the rest, the structure that is illustrated diagrammatically in Figure 3 and corresponds to the third exemplary embodiment of an MRAM memory cell according to the invention has the same construction as the first exemplary embodiment shown in Figure 2A.

Figure 4 diagrammatically illustrates the method according to the invention for fabricating a reference layer for MRAM memory cells.

A layer system is provided for the reference layer R or R', which layer system has a first layer of a material having a first Curie temperature T_C^1, which first layer can be magnetized by an external magnetic field, and a second layer of a material having a second Curie temperature T_C^2, which is significantly lower than the first Curie temperature T_C^1, which second layer can be magnetized by antiferromagnetic coupling with the first layer. The temperature axis T shows these two Curie temperatures T_C^1 and T_C^2. At the instant t1, the layer system R, R' is cooled from a temperature T0 above the first Curie temperature T_C^1 to below the first Curie temperature T_C^1, said layer system R, R' being situated in an external magnetic field B1 (arrow). In this case, the magnetization of the first layer 10 is oriented by a second-order phase transition along the field direction of the

external magnetic field B1. This presupposes that the field strength of B1 is greater than the saturation field strength of the first layer 10.

Upon further cooling, the magnetic field B1 may be switched off, and as soon as the temperature T falls below the Curie temperature T_C^2 of the second layer 11, at the instant t2, the magnetization of the second layer 11 is oriented antiparallel with respect to the first layer 10 as a result of the antiferromagnetic coupling between the two layers. This forms the artificial antiferromagnet AAF. As mentioned, and described with reference to Figure 3, the antiferromagnetic coupling of the first layer to the second layer may also be imparted by the provision of an intermediate coupling layer.

As illustrated by a dashed arrow at the instant t2 in Figure 4, for the purpose of homogenizing the magnetization distribution in the second layer 11, when passing through T_C^2, it is additionally possible to apply a magnetic field B2 whose field direction is opposite to the magnetization of the first layer 10 as long as this does not suffice to reverse the magnetization impressed in the first layer 10. This necessitates a sufficent coercitive field strength of the first layer or a sufficiently "rectangular" switching behavior of the first layer 10. In order to achieve this, the stability of the magnetization of the first layer 10 may be stabilized by means of a coupling to a natural antiferromagnet whose Neel temperature lies above the second, lower Curie temperature T_C^2.

Possible layer combinations for the first layer and the second layer may be

First layer 10 (100)	T_C^1	Second layer 11 (101)	T_C^2	Special feature
$(Co,Fe,Mn)_{80}(Si,B)_{20}$	485°C	$(Co,Fe,Mo)_{73}(Si,B)_{27}$	210°C	(soft/soft)
$(Co,Fe)_{83}(Si,B)_{17}$	415°C	$(Ni,Fe)_{78}(Si,B,C)_{22}$	260°C	(magneto-strictive)
$Tb_{20}Fe_{40}Co_{40}$	400°C	$Tb_{20}Fe_{80}$	150°C	(ferri-magnetic)

The abovementioned intermediate layer 102 illustrated in Figure 3 may comprise ruthenium, copper, gold.

List of reference symbols

1; R; R'	Reference layer
2; 12	Soft-magnetic layer
3; 13	Tunnel barrier
10; 100	First layer
11; 101	Second layer
102	Intermediate coupling layer
14	Word line
15	Bit line
T_C^1, T_C^2	Curie temperatures
B1, B2	Magnetic fields
t1, t2	Times